Journal of the Royal Society of Western Australia, 75: 3-7, 1992

Comparison of three methods of forecasting 24-hour tropical cyclone movement in the Western Australian region

Jennifer Hopwood[1] and William D. Scott[2]

[1]Department of Mathematics, University of Western Australia, Nedlands WA 6009
[2]Murdoch University, Murdoch WA 6150

Manuscript received December 1989; accepted October 1990

Abstract

Three methods of forecasting tropical cyclone tracks in the Western Australia region are discussed. One is a version of Neumann's CLIPER adapted for the region and referred to as CPLR, another is a method developed in Western Australia which uses the low-level relative vorticity field in the environment of the cyclone as a predictor, and the last is pure persistence. The three methods were used to produce 214 triplets of forecasts from best-track data for 13 cyclones and the results compared. The Wilcoxon test was used to test the significance of differences between forecasts for various subsets of cyclones. The results suggest that (a) the performances of the first two methods match that of persistence overall, and are superior when the error in the persistence forecast is greater than the mean error or when the cyclones are recurving, and (b) the second method matches CPLR overall and surpasses it with some categories of cyclones.

Introduction

The 'Tropical Cyclone Study Group' based at Murdoch University, Western Australia, for some years worked on methods of improving the forecasting of cyclone tracks in the northwest of the State. Most effort was expended on two methods that do not require upper-level wind data, which are lacking in the region; namely, a version of Neumann's (1972) CLIPER developed by Lyons and Joyce (1983) and named CPLR, and a method due to Hopwood (1978). This latter method (known as the vorticity method) uses an estimate of the vorticity in the low-level environment of the cyclone in combination with the current velocity as a predictor of the cyclone movement. CPLR uses a combination of persistence and climatology and so produces its largest errors when applied to cyclones with rapidly varying or unusual tracks. It is generally thought that cyclone motion is determined by the surrounding flow integrated in some fashion through the depth of the troposphere, but in practice it is common to take a few or even one level as representative of the whole flow, on the grounds that different levels in the atmosphere are coupled through vertical motions, which though small (except in special regions such as cumulo-nimbus cells) are not identically zero. For example, George and Gray (1976) found that the 500 mb wind averaged over an annular region between one and seven latitude degrees from the cyclone centre was the best predictor of the direction of cyclone movement while the 700 mb wind averaged in the same way was the best predictor of speed. The method CPLR cannot use explicitly any wind or pressure data at all but the persistence component incorporates it implicitly. The vorticity method also does this and in addition uses observations of surface pressure, which one would expect to reflect to some degree conditions in the overlying atmosphere.

Each method was used to produce 214 forecasts for 13 cyclones which occured in the Western Australian region during the 1979-80 and 1980-81 seasons and the resulting errors were compared with the corresponding errors produced by (a) the other method, and (b) a pure persistence forecast using average velocity over the preceding six hours as current velocity. All 642 forecasts were produced by computer routines developed by members of the Study Group. This facilitated the making of a large number of forecasts without the subjectivity of hand forecasts but, as explained later in the paper, disadvantaged the vorticity method.

CPLR

Lyons and Joyce (1983) used all available storm-track data from the Australian Bureau of Meteorology archives for storms off the north-west coast of Australia for the period 1906-1980. These data were used to produce a regression analysis (known as CLIP) with simple as well as cross terms of degrees one, two, and three following Neumann (1972). Stepwise screening regression was used to select the best combinations of predictors from the set of all possible combinations. Runs were ended when an additional predictor failed to lower the variance by at least 0.5 percent. A greater number of storm days was available than for either the Atlantic or Eastern Pacific versions of CLIPER though there were fewer storms. Also, two least-squares fits were done, one using a first-order and the other

Table 1

Twentyfour-hour errors in forecast position (nautical miles)

	CLIP	CPLR	Number of forecasts
Felix	100	95	8
Mable	97	86	8
Neil	87	81	10
Max	97	75	7

Table 2
Eight primary predictors for CPLR (after Lyons and Joyce (1983))

Predictor	Physical value	Comments
P_1	latitude at time t	
P_2	longitude at time t	
P_3	v component of storm velocity at time t	from positions @ t & t–12
P_4	u component of storm velocity at time t	from positions @ t & t–12
P_5	v component of storm velocity at time t–12	from positions @ t–12 & t–24
P_6	u component of storm velocity at time t–12 hours	from positions @ t–12 & t–24
P_7	central sea level pressure	pressure in millibars
P_8	day number	day 1 = 1 July; day 185 = 1 Jan

a second-order polynomial of the eight primary predictors (listed in Table 2). Surprisingly, the simpler linear fit proved to be more statistically significant than the second-order version and comparable in significance with CLIP. This is illustrated by a comparison, presented in Table 1, of CLIP results with results of the simpler version (here called CPLR for Climatology Persistence Linear regression) for four cyclones.

Vorticity method (AVM)

This method is based on the observation that cyclone tracks in the west Australian region appear to be affected by interaction between the cyclonic circulation and the low-level environmental flow. It requires the identification of the position of maximum value of the quantity $\xi = k.\nabla \times (k \nabla \times p)/(f\rho)$ in the 900 m flow within a 12 latitude degree radius of the cyclone; i.e. of the position where the cyclonic relative vorticity would be greatest were the flow geostrophic. Here p denotes pressure, f the Coriolis parameter, ρ density and k a unit vector in the vertical direction.

The original justification for the method was entirely empirical. A frequent feature of summertime synoptic situations in Western Australia is a trough at or near the coast, and it was known that cyclones often, but not always, move into the trough. Perusal of the records led to the conclusion that a property common to almost all instances (of those studied) of cyclones moving into the trough and absent from almost all others was cyclonic vorticity in the trough. Further investigation (Hopwood 1978) suggested that cyclones are attracted by cyclonic vorticity maxima, whether associated with a trough or not. Attempts have been made to produce a theoretical explanation of the effect, and an account of a mathematical model of a proposed mechanism is currently being prepared for publication. We give a brief summary of it here. First, a strong vorticity maximum corresponds to a region where wind and pressure fields are not in balance. The process of adjustment produces low-frequency inertial/gravity waves radiating outwards. Secondly, the very small-amplitude geopotential disturbance this produces interacts with the high Rossby-number flow in the eye-wall region of a cyclone in such a way as to cause subsidence on one side of the eyewall and upward motion on the other, thereby producing a deepening of the eye in the region of greatest upward movement and a filling on the opposite side. This produces an effective 'movement' or propagation of the storm in the direction of the enhanced upward motion.

The forecasts were made objectively using an automated computer-based scheme with the following rules:

(i) Apply a deceleration of magnitude 0.1 lat. deg./(6 hours)^2 and maintaining the initial bearing for 12 hours or until the cyclone is stationary, whichever is sooner, then

(ii) apply an acceleration of magnitude 0.1 deg.lat./(6 hours)^2 towards the vorticity maximum for the remainder of the forecast period.

(iii) If there is no vorticity maximum maintain initial velocity.

These rules follow the scheme described in Hopwood (1978) except that the forecast is based on acceleration rather than velocity. They incorporate a measure of persistence but no climatology. Observations of the behaviour of west Australian cyclones between 1978 and 1986 and the theoretical work referred to above suggest that the magnitude of the acceleration ought to depend on the strength of the vorticity maximum and the strength of the cyclone. However, for practical reasons and to maintain an objective forecast the forecasts were all made automatically using the same magnitude of acceleration. The given value of the acceleration was chosen because in a preliminary analysis of a sample of six cyclones it gave the best mean result. These cyclones were not included in the set used for the comparison with CPLR.

Calculation of vorticities from standard meteorological data is difficult because it involves estimating second-order differences in a pressure field. An automated scheme developed by Scott *et al.* (1982) uses optimal triangular nets to produce a 'best set' of vorticities from a set of pressure and temperature data (Magnus *et al.* 1983). Quite good forecasts were produced but unfortunately the procedure proved too time-consuming for operational use. Therefore the scheme was abandoned and instead Surface II (Sampson 1975) was used to produce contours of 900 m pressure and temperature on a 2.5 degree grid. Surface II is an algorithm which interpolates to produce data on a square pattern in a Cartesian framework of latitude and longitude. Finite differences are then used to estimate the vorticity at each grid-point. One effect of this latter approach is to smooth out the vorticity field considerably. A comparison of some of the results with corresponding hand-drawn 900 m charts suggests that on some occasions the smoothing even causes the position of the vorticity maximum to be wrongly identified, assuming that the position on the hand-drawn chart is correct. The Automated Vorticity Method (hereinafter known as AVM) thus enters the comparison contest considerably handicapped.

Comparison of methods

The three forecasting schemes were used to produce 214 24-hour forecasts for 13 cyclones using synoptic data for 0500 GMT, 1100 GMT, 1700 GMT and 2300 GMT. A list of the cyclones is given in Table 3. Each forecast position was compared with the corresponding best-track position, and forecast position and direction errors produced for each

Table 3
Cyclones used in the comparison

Cyclone	Period		
Amy	6 — 11	January	1980
Brian	20 — 27	January	1980
Clara	22 — 27	January	1980
Dean	30	January	1980
Enid	14 — 16	February	1980
Gloria	21 — 27	March	1980
Carol	13 — 23	December	1980
Dan	16	December	1980
Felix	23 — 29	December	1980
Edna	21 — 25	December	1980
Mabel	13 — 19	January	1981
Neil	26 — 5	Feb/Mar	1981
Max	14 — 17	March	1981

scheme. The non-parametric Wilcoxon test was applied to various subsets of errors in order to test the significance of the differences between the errors. This test, which takes account of the magnitude as well as the sign of the differences, requires that the data be serially independent. Independence was tested for by using the run test on the set of error differences for each cyclone. A run is a set of successive differences of the same sign and either an abnormally high or an abnormally low number of runs indicates lack of independence. The results of the test led us to accept the hypothesis that the data are independent. This is not to say, of course, that the positions of a cyclone at two times six hours apart are not correlated, but rather that the success of one forecasting method relative to another at one time is independent of its success at a time six hours before or after.

Tables 4 to 8 show the results of the comparison of errors: table 4, all cyclones in the sample; Table 5, all cyclones at latitudes poleward of 20°S and all cyclones equatorward of 20°S at forecast time: Table 6, all cyclones which were moving eastward and all cyclones which were moving westward at forecast time: Table 7, all cyclones for which the error in the persistence forecast was greater than the mean (101 nautical miles), and Table 8, all recurving cyclones. This last category consisted of the four cyclones which changed from westward movement at forecast time to eastward movement at some time during the following 24 hours. Only the first such forecast for each cyclone was counted because subsequent forecasts were not independent and so the sample was too small to justify application of a statistical test.

Each table shows the mean position error (that is, the mean distance between forecast and actual position), the mean error in forecast direction, latitude and longitude, the standard deviations of the position errors, and P, which is the probability of obtaining a Wilcoxon test statistic less than the one actually obtained, under the null hypothesis that both sets of errors come from populations with the same mean. Square brackets indicate that only the magnitude of the quantity is considered. Differences were calculated by subtracting the error of the method with the smaller mean error from the corresponding error of the method with the larger mean error. The test statistic was the sum of the negative ranks; that is, a small value of P indicates that the method with the smaller mean error is probably superior. A positive direction error means that the forecast position lay to the right of the actual track; a positive latitude (longitude) error means that the forecast position was too far to the south (east). Units are nautical miles and degrees.

Table 4
All cyclones, 214 forecasts.

Mean Error in	CPRL	AVM	Persistence
Position	101.5	104.5	101.3
[Direction]	23.9	26.0	23.9
[Latitude]	1.0	1.1	1.1
[Longitude]	1.2	1.2	1.1
Direction	−2.2	3.7	3.0
Latitude	0.1	−0.3	−0.1
Longitude	0.2	0.2	−0.2
S.D. Dist	69.9	66.6	70.2

P	Position	|Direction|
AVM vs CPLR	.09	.10
CPLR vs Persistence	.50	.74
AVM vs Persistence	.05	.07

Table 5
The effect of latitude

	Cyclones poleward of 20°S 32 forecasts			Cyclones equatorward of 20°S 182 forecasts		
Mean error in	CPLR	AVM	PER	CPLR	AVM	PER
position	158.5	132.7	138.3	91.4	99.5	94.8
[Direction]	−32.3	27.3	28.0	22.4	25.7	23.2
[Latitude]	1.6	1.6	1.6	0.9	1.0	1.0
[Longitude]	2.0	1.5	1.5	1.1	1.1	1.1
Direction	−6.0	11.1	13.1	−1.5	2.4	1.2
Latitude	0.1	0.0	0.5	0.1	−0.4	−0.2
Longitude	0.8	−0.9	−1.1	0.0	0.5	0.0
S.D. Dist	76.1	61.2	67.4	63.6	66.3	68.7

P	Position	|Direction|	Position	|Direction|
AVM vs CPLR	.05	.05	.01	.01
CPLR vs Persistence	.09	.09	.17	.14
AVM vs Persistence	.15	.12	.01	.02

Table 6
The effect of east-west movement

	Cyclones moving east 51 forecasts			Cyclones moving west 162 forecasts		
Mean Error in	CPLR	AVM	PER	CPLR	AVM	PER
Position	139.3	130.0	132.8	89.3	96.3	91.2
[Direction]	35.8	29.9	34.6	19.3	23.0	20.5
[Latitude]	1.5	1.6	1.4	0.9	1.0	1.0
[Longitude]	1.7	1.4	1.5	1.0	1.1	1.0
Direction	19.5	9.5	−2.2	−5.7	6.4	4.6
Latitude	−0.1	−0.5	−0.1	0.1	−0.3	0.0
Longitude	−0.8	−1.1	0.1	0.3	0.4	−0.3
S.D. Dist	83.6	83.5	95.7	59.9	52.8	56.2

P	Position	|Direction|	Position	|Direction|
AVM vs CPLR	.04	.04	.006	.005
CPLR vs Persistence	.13	.13	.20	.04
AVM vs Persistence	.21	.04	.01	0

Table 7
The effect of 'difficulty'

Cyclones for which persistence error greater than 101 nmi 93 forecasts

Mean error in	CPLR	AVM	Persistence
position	149.4	155.3	160.1
[Direction]	31.9	33.6	32.4
[Latitude]	1.5	1.7	1.7
[Longitude]	1.7	1.7	1.8
Direction	−5.6	3.8	3.0
Latitude	0.1	−0.3	0.0
Longitude	0.2	0.0	−0.3
S.D. Dist	72.0	67.6	66.8

P	Position	|Direction|
CPLR vs Persistence	.03	.25
AVM vs Persistence	.047	.32

Table 8
Recurving cyclones, four forecasts

Mean Position Error	
97.4	CPLR
82.5	AVM
109.0	Persistence

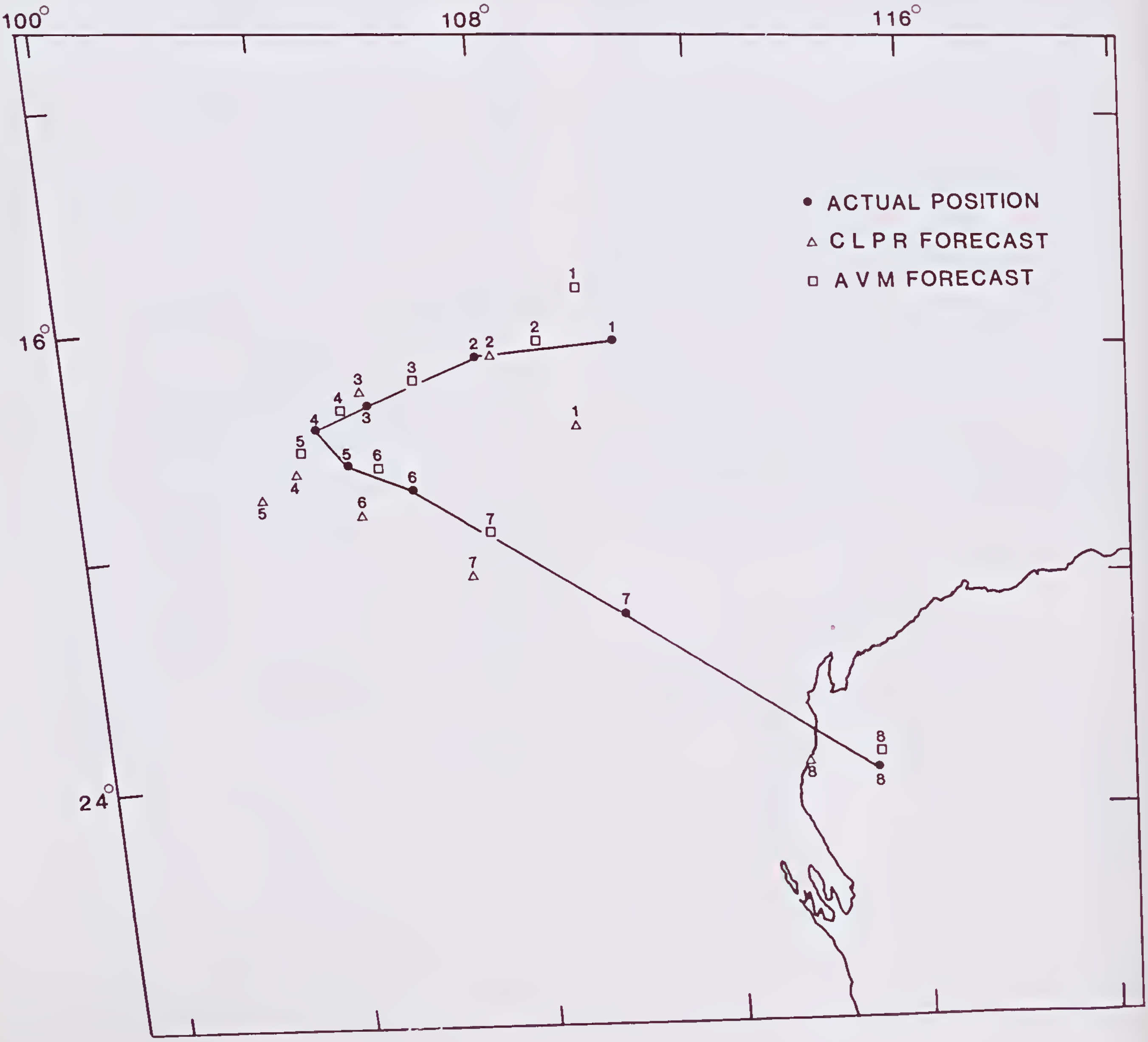
Overall there appears to be little to choose between the methods. The CPLR and persistence mean position errors are slightly less than the AVM error but the standard deviations are larger. In both cases the sum of the mean error and one standard deviation is 171 nautical miles. The AVM position error was greater than this value on 22 occasions, on eight of which the CPLR error was greater still. The CPLR position exceeded 171 n mi on 26 occasions, on seven of which AVM was worse. The Wilcoxon test indicates that the differences are not significant at the 5% level. The closeness of the means might lead one to suppose that AVM and especially CPLR are merely reproducing the pure persistence forecasts. An inspection of the results of individual forecasts shows that this is not the case. For instance, the AVM and persistence errors for Felix at 2300 GMT on 25 December were 72 and 30 n mi respectively, and for Neil at 1100 GMT on 28 February were 12 and 52 n mi. The CPLR and persistence errors for Max at 2300 GMT on 17 March were 34 and 119 n mi respectively, and for Neil at 1500 GMT on 6 March were 72 and 13 n mi.

All three methods produce large errors when cyclones are at latitudes polewards of 20°S at forecast time but AVM appears to be superior to CPLR. The Wilcoxon test shows that the differences are significant (just) at the 5% level. The AVM error is slightly less than the persistence error but the difference is not significant. The same remarks apply to eastward-moving cyclones, with the added observation that the standard deviation of persistence errors is larger (95.7 n mi) than that of either CPLR (83.6) or AVM (83.5), and the AVM direction forecasts are significantly better than both CPLR and persistence direction forecasts.

CPLR and persistence are not significantly different and are clearly superior to AVM when the cyclone is at a latitude equatorward of 20°S or westward-moving. All three methods do better with this category of cyclones relative to their own performance at higher latitudes or with eastward movement. Both AVM and CPLR did significantly better (at the 5% level) on those occasions when the persistence error was greater than its mean value, with CPLR being the better of the two. This suggests that the non-persistence components of both these methods are exhibiting skill with these 'difficult' tracks.

Pure persistence by definition cannot forecast recurvature, and CPLR cannot forecast recurvature in climatologically unusual positions. AVM was the best performer with

Figure 1 Forecast position for cyclone Neil produced by the CPLR and AVM methods, shown with the corresponding best-track positions. All positions are for 0500 GMT. The position numbered 1 is for February 26, 1981.



the four recurving cyclones (mean error 82.5 n mi) followed by CPLR (mean error 97.4 n mi) and persistence (mean error 109 n mi). The sample is too small to justify application of tests of significance. A sample result is displayed in Fig 1, which shows the track of cyclone Neil. Note that the CPLR and persistence forecasts tend to overshoot the point of recurvature whereas AVM more closely follows the best track.

Conclusions

If the cyclones in our sample are representative of cyclones in the Western Australian region then in most cases it would be difficult to improve on persistence 24-hour forecasts. This result was not entirely unexpected in view of the findings of Holland and Pan (1981) and Holland (1983, 1984) that tracks of west Australian cyclones are less variable than those of cyclones in the eastern Australian region. Both CPLR and AVM are better than persistence when the tracks are difficult in the sense that the error of a persistence forecast is worse than the mean persistence error. In view of the fact that AVM matched CPLR and persistence overall and in some categories surpassed them, and this occurs in spite of the handicaps previously described, we consider that it has exhibited some worth. It is likely to be most useful for cyclones in higher latitudes and for forecasting unusual behaviour which CLIPER-type methods cannot handle. We are also of the opinion that these results represent a lower bound on the accuracy of the method and it is expected that incorporation of the strength of the vorticity maximum into the forecasting rule would be a significant improvement, in spite of the difficulty of obtaining accurate measurements of this quantity.

Acknowledgements: We would like to thank the Director of the Australian Bureau of Meteorology for making available the data used for the automated forecasts. The members of the 'Tropical Cyclone Study Group' at Murdoch University are also gratefully acknowledged: I. Foster, W. Hare, C. Joyce, P. Kloeden, T. Lyons, and E. Magnus. The present paper has evolved from one presented at the Second Australian Conference on Tropical Meteorology (Hopwood & Scott, 1985).

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